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Optical Phase and Scintillation at AMOS

~~Electronics Research Laboratory~~
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Interim Report

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We present calculations of both the log-amplitude variance and phase coherence diameter for stellar sources at AMOS and compare our results to the measured value of the corresponding quantities, as performed by AVCO on the nights of November 17, 18, and 21, 1975. Our calculations are based, in part, on R. E. Hufnagel's recent model of atmospheric turbulence. We find fairly good agreement with the scintillation data, the agreement with the phase data being only fair to good. Although the results presented here are encouraging, more data

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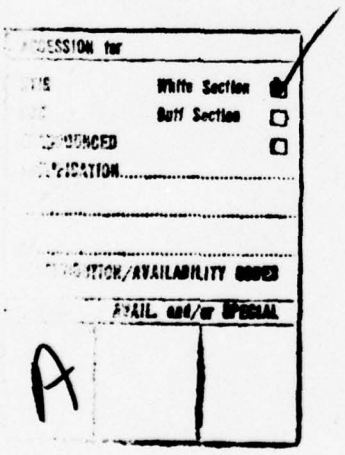
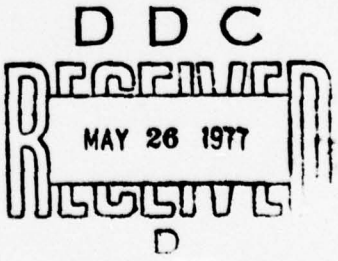
comparison is needed before the validity for general use at AMOS of the turbulence model used here can be established.

PREFACE

We acknowledge with appreciation D. Chang of The Aerospace Corporation for performing the numerical calculations, M. Miller of AVCO who supplied us with the relevant experimental data, and Maj. J. Madura of SAMSO who provided us with wind speed data.





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I. INTRODUCTION

The purpose of this report is to seek to determine if any correlation exists between measured values of both stellar scintillation and phase coherence and the corresponding values predicted from a recent model of the atmospheric turbulence profile. Specifically, we employ here Hufnagel's[1] recent model of the index structure constant profile $C_n^2(h,V)$, where h is the altitude above mean sea level and V is a root mean square wind speed (defined below) to calculate both the variance and covariance of the log-amplitude and phase coherence diameter r_o of an optical wave due to a stellar source. We then compare these quantities to the corresponding quantities as measured by AVCO and AMOS during November 1975.

We first discuss Hufnagel's recent model of C_n^2 and present expressions for the appropriate wave statistical quantities. Using measured values of the wind speed parameter V for the appropriate dates of the experiment, we then proceed in Section IV to calculate the normalized log-amplitude variance and compare with the corresponding values, as measured by AVCO. For the three experimental dates considered, fairly good agreement is obtained.

In the design and deployment of the AMOS compensated imaging system, it is necessary to have knowledge of the statistical characterization of the phase coherence diameter of the atmosphere r_o of an optical stellar source. In Section IV we present the results of our calculation of r_o and compare with AVCO's experimental results. The present calculation of r_o is based on Hufnagel's recent model of C_n^2 together with a low altitude C_n^2 model (i.e., 0—3 km above the AMOS site) abstracted from the experimental results of Bufton[2] and Koprov and Tsvang[3]. Our calculated values of r_o are a little larger than AVCO's measured average values, although not as large as AVCO's value of r_o as calculated on the basis of measured turbulence profiles.

Although the present results are encouraging, more comparison with experimental data is needed before the validity of the turbulence model used here can be established. However, at this point we are cautiously optimistic.

II. ATMOSPHERIC TURBULENCE PROFILE

Recently R. E. Hufnagel[1] presented an empirical model for the altitude profile of the index structure function C_n^2. In its full generality, the random turbulence version of the Hufnagel turbulence model has the form (in units of $m^{-2/3}$)

$$C_n^2(h) = 5.98 \times 10^{-23}(V/27)^2 h^{10} e^{-h} + 10^{-16} \times e^{-h/1.5} \exp[r(h,t)], \quad h > 3 \text{ km} \qquad (1)$$

where h is in kilometers above mean sea level, V is the root mean square wind speed in meters/sec in the 5 to 20 km altitude range, i.e.,

$$V = \left[\frac{1}{15 \text{ km}} \int_{5 \text{ km}}^{20 \text{ km}} v^2(h)\, dh\right]^{1/2}, \qquad (2)$$

where v(h) is the wind speed profile in m/sec. The quantity r(h,t) is a guassian random variable which depends on altitude and time. As defined by Hufnagel, r has zero mean and a correlation function given by

$$\langle r(h + h', t + \tau) r(h,t) \rangle = A(10h') \exp(-\tau/300) + A(h'/2) \exp(-\tau/4800) \qquad (3)$$

where t is time measured in seconds and the function A is given by

$$\begin{aligned} A(x) &= 1 - |x|, \quad |x| \leq 1 \\ &= 0, \quad |x| > 1 \end{aligned} \qquad (4)$$

In some cases it may be more convenient computationally to use an exponential decay function, i.e., $A(x) = \exp(-|x|)$.

As is discussed below, the available data does not warrant the use of the full random model of C_n^2. Accordingly, we employ the non-random model, obtained by taking the ensemble average of Eq.(1). We obtain ($\langle e^r \rangle = e \cong 2.72$)

$$C_n^2(h,V) = 5.98 \times 10^{-23}(V/27)^2 h^{10} e^{-h} + 2.72 \times 10^{-16} e^{-h/1.5} \qquad (5)$$

where V is given by Eq. (2). As discussed by Hufnagel[1], V appears to be normally distributed about some average value. For example, for the state of Maryland, V appears to be normally distributed with an average value of 27 m/sec and a standard deviation of 9 m/sec. Below we use the value of V obtained from the wind speed profiles for the dates of the measurements, as supplied by the Air Weather Service.

Strictly speaking, Eq. (1) or (5) is valid for $h \gtrsim 3$ km. Since the measurements we performed at AMOS, i.e., at an altitude of 3 km, Eq. (5) will suffice for the present analysis. However, for completeness we present a model developed from the empirical data of Koprov and Tsvang[3], and J. Bufton[2] for the value of C_n^2 at altitudes below 3 km:

$$C_n^2 = \begin{cases} 7.0 \times 10^{-14} h^{-4/3} & , \quad 10 \text{ m} < h < 100 \text{ m} \\ 1.5 \times 10^{-16} & , \quad 100 \text{ m} < h < 500 \text{ m} \\ 1.5 \times 10^{-16} - 1.125 \times 10^{-16}\left(\frac{h - 500}{500}\right) & , \quad 500 \text{ m} < h < 1000 \text{ m} \\ 3.75 \times 10^{-17} + 7.95 \times 10^{-17}\left(\frac{h - 1000}{1000}\right) & , \quad 1000 \text{ m} < h < 2000 \text{ m} \\ 1.17 \times 10^{-16} - 5.85 \times 10^{-17}\left(\frac{h - 2000}{2000}\right) & , \quad 2000 \text{ m} < h < 3000 \text{ m} \end{cases} \qquad (6)$$

The model presented above is simple in many respects. It does not explicitly account for possible high turbulence peaks generated at frontal interfaces or sharp inversion layers. And, conceivably the numerical coefficients in model should be different over mountaineous terrain. Nevertheless, it does seem to yield reasonable agreement with most of the observed stellar scintillation measurements taken in the past. The appeal of the model lies in the fact that there is only one parameter, the root mean square wind speed V, which characterizes the altitude dependence of C_n^2. This parameter is readily available for many experimental sites

and in particular it is available for AMOS. Finally, we note that it is expected that the largest variability of C_n^2 is obtained near the ground, the high altitude turbulence being insensitive to effects of local terrain. As is discussed below, the effects of low altitude turbulence have little effect in producing scintillation. However, both low and high altitude turbulence are important in producting optical phase distortions.

III. IRRADIANCE STATISTICS

In all cases considered here we are in the regime of weak optical scintillation; that is, we are in unsaturated regime of scintillation where the results of the Rytov approximation apply. The regime of weak scintillation is such that the normalized variance of log-amplitude, σ_ℓ^2, is much less than unity. In this regime it is known[4] that the probability distribution of irradiance is log-normal (i.e., the natural logarithm of irradiance is normally distributed); that is, the probability density of irradiance is given by

$$P(i) = \frac{1}{\sqrt{2\pi \ \ell n \left(\sigma_I^2 + 1\right)}} \left(\frac{1}{i}\right) \exp\left\{ - \frac{\left[\ell n\, i + 1/2 \ \ell n \left(\sigma_I^2 + 1\right)\right]^2}{2 \ \ell n \left(\sigma_I^2 + 1\right)} \right\} \tag{7}$$

where

$$i = \frac{I}{\langle I \rangle} \quad , \tag{8}$$

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \quad , \tag{9}$$

I is the instantaneous value of irradiance, and angular brackets denote the ensemble average. Thus, i is the instantaneous value of irradiance normalized by its mean, and σ_I^2 is the normalized variance of irradiance. Examination of Eq. (7) reveals that the probability distribution of normalized irradiance is characterized by the single parameter σ_I^2, the normalized variance of irradiance.

For log-normal statistics, the normalized variance of irradiance for a point receiver is related to the variance of log-amplitude, σ_ℓ^2, by the relation

$$\sigma_I^2 = \exp(4\ \sigma_\ell^2) - 1$$
$$\approx 4\ \sigma_\ell^2\ ,\quad \sigma_\ell^2 << 1 \tag{10}$$

The introduction of the quantity σ_ℓ^2 as the basic parameter is operationally useful as this is the quantity that is usually measured. Thus for a given value of σ_ℓ^2, the probability distribution of irradiance is determined completely.

We next present expressions that relate the log-amplitude statistics to the index structure profile, optical wavelength and propagation path. For weak scintillation conditions the log-amplitude correlation function for a point (i.e., stellar) source at infinity is given by[4]

$$B_A(\rho) = 4\pi^2 k^2 \sec\theta^{11/6} \int_{h_1}^{\infty} C_n^2(h)dh \int_0^{\infty} J_o(K\rho)\ \Phi_n(K) \sin^2\left[\frac{K^2(h-h_1)}{2k}\right] KdK \tag{11}$$

where ρ is the separation in a plane transverse to the mean direction of propagation, θ is the zenith angle, h_1 is the altitude of the receiver, k is the optical wave number (= $2\pi/\lambda$, where λ is the optical wavelength), J_o is the Bessel function of zero-order of the first kind, $C_n^2(h)$ is the index structure profile, and $\Phi_n(K) \simeq 0.033\ K^{-11/3}$.

The variance of log-amplitude is then given by

$$\sigma_\ell^2 = B_A(0) = 4\pi^2 k^2 \sec\theta^{11/6} \int_{h_1}^{\infty} C_n^2(h)\ dh \int_0^{\infty} \Phi_n(K) \sin^2\left[\frac{K^2(h-h_1)}{2k}\right] KdK$$

$$\cong 0.563\ k^{7/6} \sec\theta^{11/6} \int_{h_1}^{\infty} C_n^2(h)(h-h_1)^{5/6}\ dh \tag{12}$$

Examination of Eq. (12) reveals that owing to the $h^{5/6}$ weighting function in the integrand, the value of σ_ℓ^2 is determined primarily from high altitude turbulence. Examination of Eqs. (5) and (12) reveals that for $V \gtrsim 10$ m/sec the main contribution to σ_ℓ^2 is determined by the turbulence near the tropopause, i.e., at $h \sim 10$ km. The integrand of Eq. (12) has a relative maximum for h = 10.83 km, falling to one-half its maximum value at $h \simeq 7.5$ and 15.5 km.

Equation (12) for σ_ℓ^2 pertains to the statistics of irradiance at a point. As the experiments at AMOS were performed with a finite size receiving aperture, it is necessary in our anlaysis to account for aperture smoothing. As is discussed below, the effects of aperture smoothing are determined not only by the log-amplitude variance σ_ℓ^2 but also by the shape of the correlation function $B_A(\rho)$. As such, it will also be necessary to compute the full correlation function $B_A(\rho)$ for $\rho \lesssim D$, where D is the diameter of the receiving aperture (= 35.6 cm for the AMOS experiments). This calculation is discussed in more detail later on in this section.

Upon substituting Eq. (5) into Eq. (12), we find that the log-amplitude variance at a point is given by

$$\sigma_\ell^2 \cong \left[4.14 \times 10^{-2} \left(\frac{V}{27}\right)^2 + 2.48 \times 10^{-3}\right] \left[\frac{0.5}{\lambda(\text{micron})}\right]^{7/6} \sec\theta^{11/6}$$

$$= 4.14 \times 10^{-2} \left(\frac{V}{27}\right)^2 + 2.48 \times 10^{-3}, \quad \text{for } \lambda = 0.5 \ \mu\text{m}, \ \theta = 0 \qquad (13)$$

and is plotted in Fig. 1 as a function of V for the case $\lambda = 0.5$ μm and $\theta = 0$. In order to compare with experiment, one must correct these values for the smoothing effect of the finite size collecting aperture.

As alluded to above, scintillation measurements performed with a finite sized collector include an aperture smoothing effect referred to in the literature as the aperture averaging effect. Thus, the log-amplitude variance obtained from a collector of diameter D, $\sigma_\ell^2(D)$, is related to the corresponding point log-amplitude variance by

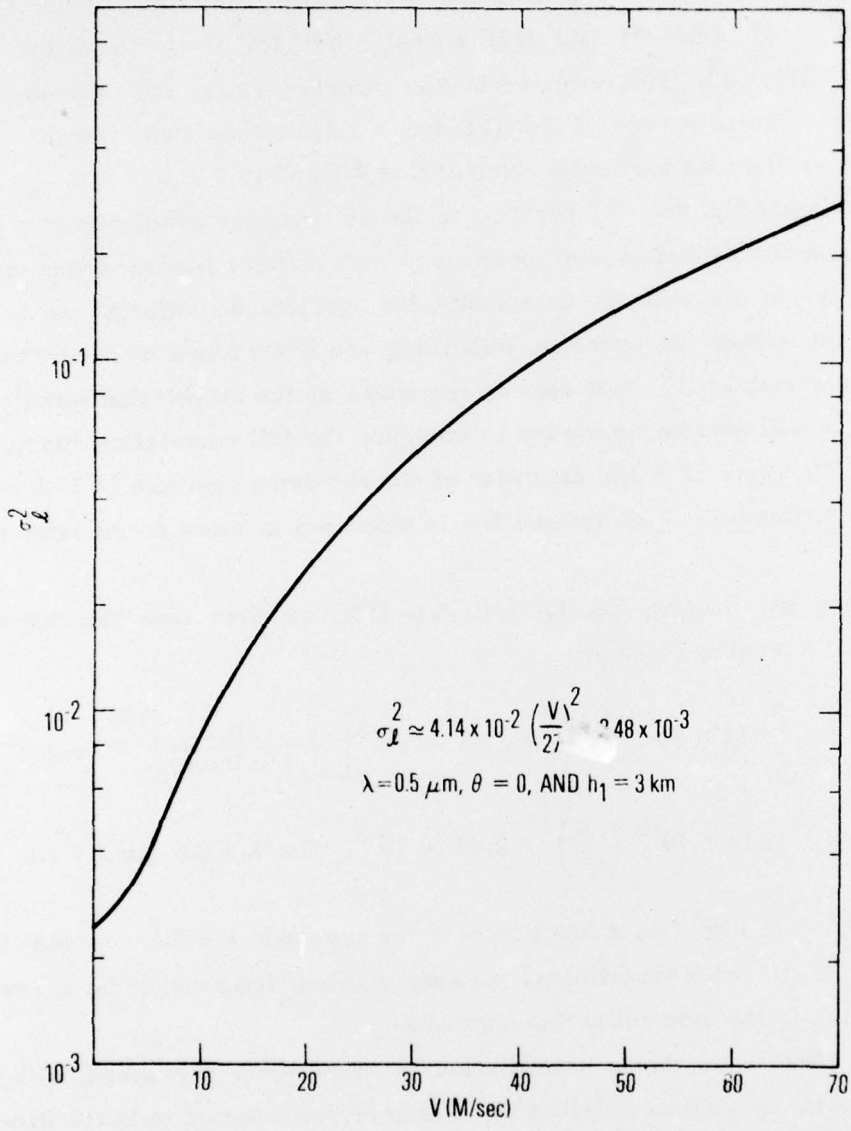

Fig. 1. Calculated value of the log-amplitude variance at a point as a function of the rms wind speed

$$\sigma_\ell^2(D) = A \ \sigma_\ell^2 \tag{14}$$

where the aperture averaging factor $A(\leq 1)$ is given by[5] (we assume here that the collecting aperture is circular)

$$A = 8 \int_0^1 \frac{C_I(DX)}{C_I(0)} \ M_L(x) \ x dx \tag{15}$$

where

$$M_L = \frac{2}{\pi} \left[\cos^{-1} x - x \ \sqrt{1 - x^2}\right], \ 0 \leq x \leq 1$$

$$= 0 \quad , \quad x > 1 \tag{16}$$

$$C_I(\rho) = \exp \left[4 B_A(\rho)\right] - 1 \tag{17}$$

and $B_A(\rho)$ is given by Eq. (11). Examination of Eqs. (11) and (17) reveal that the value of A depends on the characteristic correlation length of the log-amplitude correlation function p_ℓ. For $D << p_\ell$, $A \simeq 1$ and there is no aperture averaging effect, the receiver is essentially a point receiver. On the other hand, for $D \gtrsim p_\ell$, several "independent" fluctuations with differing signs are collected, and they partially compensate one another leading to a value of $A < 1$. For uniform turbulence condition the amplitude correlation length is of the order $\sqrt{\lambda L}$, where L is the path length and λ is the optical wavelength.

Examination of Eqs. (15) and (17) reveal that for $B_A(0) = \sigma_\ell^2 < 1$ the value of A depends on the form of the normalized log-amplitude covariance function $b_A(\rho) = B_A(\rho)/\sigma_\ell^2$ only. For values of V greater than about 10 m/sec the dominant contribution to $b_A(\rho)$ results from the turbulence in the tropopause, i.e., the first term on the right-hand side of Eq. (1). In the experiments discussed below the value of V is in the 20 to 30 m/sec range. As a result, it can be shown for this case that $b_A(\rho)$ is nearly a universal curve; that is, $b_A(\rho)$ is independent of V for $V \gtrsim 10$ m/sec. This implies that A is nearly independent of V. These results have been confirmed numerically for all values of V that were obtained in the AMOS experiments. We find that $A \simeq 0.019$ for the 14-inch diameter collector used at AMOS.

AVCO has performed scintillation measurements using a star sensor built by NOAA Environmental Research Laboratory. This instrument consists of a 35.6 cm Schmidt-Cassegrain telescope. When a stellar source is received through this system, measurements of the spatial frequency content of the atmospherically produced scintillation pattern are obtained. Details of the experimental apparatus and results obtained are reported elsewhere[6]. We have chosen three separate days to compare with. These days were chosen because the environmental profile $C_n^2(h)$ was also measured independent of the optical measurements. Further details of the C_n^2 measurements are also given in Ref. 6.

The nights chosen to compare our results to experiment are Nov. 17, 18 and 21, 1975. The experiments were generally run between 1900 to 2400 hours local time.

The wind speed data, obtained through Maj. John Madura of SAMSO, was taken at Hilo, Hawaii, at 2400 hours. Although Hilo, Hawaii, is about 100 miles from Maui, it is not expected that the values of V over Maui were significantly different than those over Hawaii, owing to the fact that the main contribution to V is at high altitude (5—15 km) and the terrain between the two islands is primarily open ocean. The value of V obtained are 21.3, 20.5, and 30.8 m/sec for Nov. 17, 18, and 21, respectively.

In Table 1 we have tabulated the values of σ_ℓ^2 obtained by AVCO at 0.5 μm and the results of our calculations.

TABLE 1

Log-Amplitude Data Comparison

(D = 35.6 cm, A $\simeq$ 0.019)

	σ_ℓ^2, AVCO		σ_ℓ^2, Aerospace Corp., $\theta = 0$	
Date	Range $\times 10^{-4}$	Average, $\times 10^{-4}$	Average, $\times 10^{-4}$	V (m/sec)
Nov 17	2.79 - 18.20	7.92	5.37	21.3
Nov. 18	2.28 - 5.03	3.76	4.95	20.5
Nov 21	5.17 - 8.21	6.00	10.70	30.8

The AVCO data presented in the second column is a summary of twenty-minute log-amplitude variance measurements. The theoretical zenith angle dependence of $(\sec \theta)^{11/6}$ was not removed by AVCO because "all data was collected on stars at low zenith angle (typically 10—20°, 30° maximum) and this effect should not be large." Our results are based on zenith propagation, i.e., $\theta = 0$.

No attempt was made by AVCO to compare their optical scintillation results to the corresponding results obtained from the C_n^2 profile that was measured on the dates of the experiments. Furthermore, an analysis of the variance of the σ_ℓ^2 was not performed, although enough data was recorded so that this information can be readily obtained. (Note: AVCO is in the process of doing this.*)

Examination of Table 1 reveals that our calculated values of σ_ℓ^2 are in good agreement with AVCO's measured values; in two cases the calculated value is in the experimental range, while in the third care it is about 25% high. In view of the fact that some zenith angle biasing may be present $[\leq (\sec 30)^{11/6} = 1.3]$ and the experiments were performed over several hours on each night, we feel that the results obtained here are encouraging enough to warrant further comparisons as more data is made available. We are in the process of doing this.

IV. PHASE COHERENCE STATISTICS

As is well known, the mutual coherence function (MCF) of the complex field due to a point source above the atmosphere is a central quantity in the evaluation of the AMOS compensated imaging system. Here we relate the coherence diameter r_o to the rms wind speed V and compare these results to the experimental values obtained by AVCO during Nov. 17, 18, and 21, 1975.

The MCF can be written as

$$M(r) = \exp\left[-3.44\left(\frac{r}{r_o}\right)^{5/3}\right] \tag{18}$$

where the coherence diameter r_o is given by

*M. Miller, AVCO Everett Research Lab., private communication.

$$r_o \cong \left[\frac{3.44}{1.45\, k_v^2 \sec\theta \int_{h_i}^{\infty} C_n^2(h)\, dh} \right]^{3/5} \qquad (19)$$

Examination of Eq. (19) reveals that in contrast to the case of scintillation, the coherence diameter depends both on low and high altitude turbulence (the weighting factor in the integrand of Eq. (19) being unity in the present case.

AVCO's measured turbulence profiles averaged over the complete data runs taken on 17, 18, and 21 Nov. 1975 are shown in Fig. 2. The lowest height (15 m) data points were obtained from the ground-based microthermal sensors. Data from 37 m to 2.5 km were provided by NOAA from a reduction of their (nighttime) airborne microthermal data. The line segments from 1 km to 24 km were derived from Star Sensor data and represent the approximate width of the weighting functions used in the data reduction. The horizontal scale is in height above the observatory which is at an altitude of approximately 10,000 ft. The tropopause height was determined from rawindsonde temperature profiles obtained from the two Hawaiian Weather Bureau stations.

For comparison, the turbulence profile used for our calculation, i.e., Eqs. (5) and (6) are given by the dashed curve in Fig. 2, along with the value of V for the date in question.

We have computed r_o based on the assumption that the plane of the receiver is 10 m above local ground and the use of Eq. (5) for high altitude turbulence and Eq. (6) for turbulence near the ground. The numerical results for $\theta = 0$ are plotted in Fig. 3 as a function of V (upper curve). Also, we have computed the values of r_o based on Eq. (5) above and these results are also shown in Fig. 3 (lower curve). Examination of Fig. 3 reveals that for $5 \lesssim V \lesssim 15$ m/sec the values of r_o obtained by including turbulence near the ground are within a factor of two to that obtained otherwise. For larger values of V, the corresponding values of r_o approach one another asymptotically. This is expected since for large values of V the main contribution to r_o results from turbulence values at high altitudes.

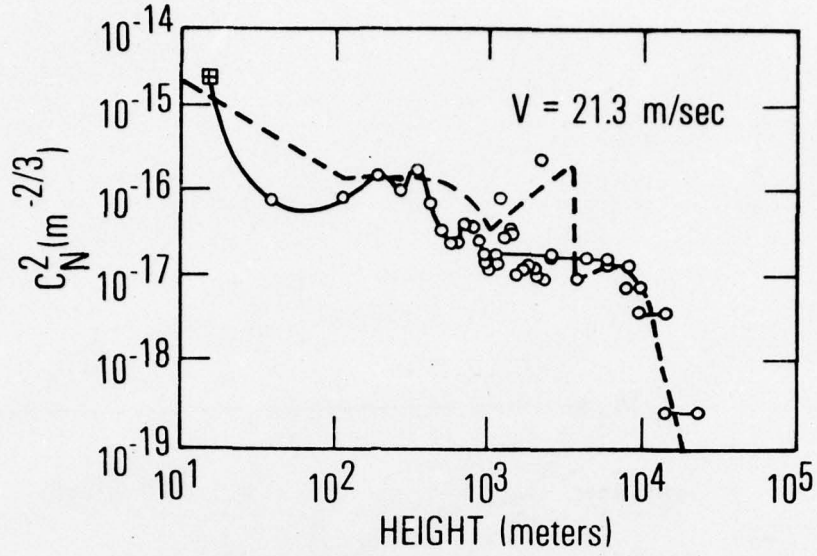

Fig. 2a. Turbulence Profile vs Height Above the Observatory - 17 November 1975. Ground Based Microthermal Data = □; Airborne Microthermal Data = +; Star Sensor Data = ++. Estimated tropopause height of 11-15.5 km. The dotted curve is the sum of Eqs. (5) and (6) for the value of V indicated

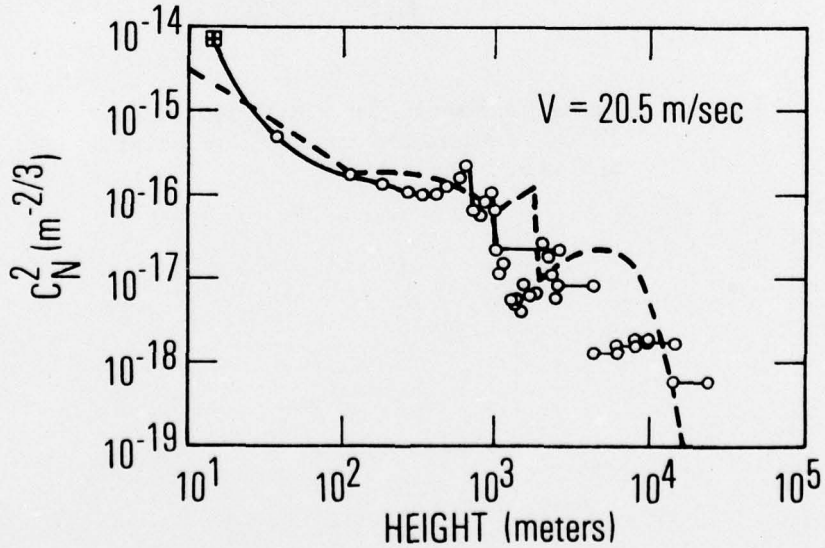

Fig. 2b. Same as Figure 2b for 18 November 1975. Estimated tropopause height of 9-15.5 km.

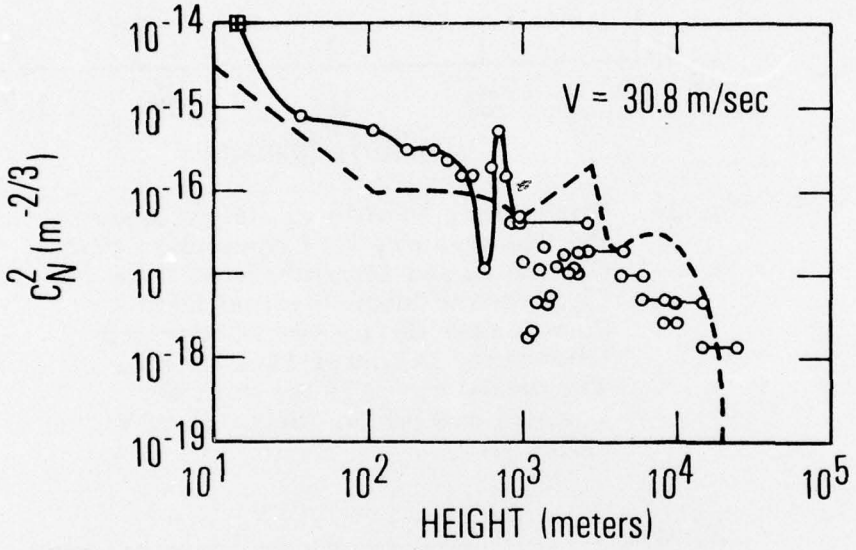

Fig. 2c. Same as Figure 2b for 21 November 1975. Estimated tropopause height of 9-15.5 km.

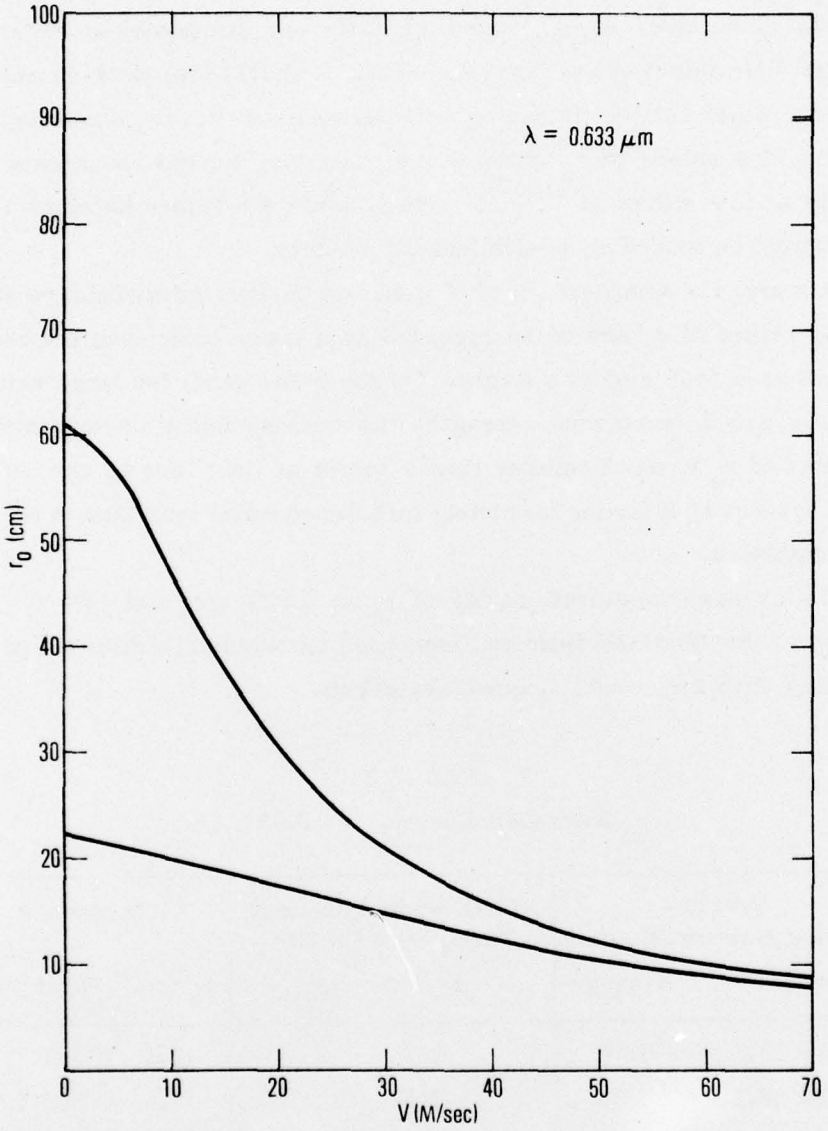

Fig. 3. The phase coherence diameter $\lambda = 0.633\,\mu m$ as function of rms wind speed. The upper curve is based on Hufnagel's model for high altitude turbulence while the lower curve includes the contribution from low altitude turbulence as given by Eq. (16).

The use of Eq. (6) for low altitude turbulence values may not be representative of the conditions above the AMOS site as it was developed from measurements made over level ground at different geographical location and averaged over different times of the year. Thus, it should represent, in our opinion somewhat of a worst case estimate of turbulence above local ground and is used here as such. The values of r_o obtained by employing Eq. (6) represents a worst case estimate at low values of $V(\lesssim 15$ m/sec), while the values obtained for large values of V should be looked upon with less uncertainty.

In summary, for small values of V (i.e., low integrated turbulence strength) the predicted values of r_o are to be regarded as a lower limit with the real value being as much as a factor of two larger. On the other hand, for large values of V (i.e., high integrated turbulence strength) the corresponding uncertainty in the predicted value of r_o is much smaller than a factor of two; that is, the confidence by which we predict r_o is larger for strong turbulence conditions than it is for weak turbulence conditions.

AVCO's average measured values of r_o at 0.633 μm and $\theta = 0^o$ and the corresponding values obtained from the measured turbulence profiles are presented in Table 2 along with the results of our calculations.

TABLE 2

r_o Data Comparison, $\lambda = 0.633$ μm

Date	AVCO Seeing Monitor, r_o (cm)		AVCO, From Measured Turbulence Profile,	Aerospace	
	Range	Average	r_o (cm)	r_o (cm)	V (m/sec)
Nov 17	9.3 - 13.5	10.4	25.7	17.1	21.3
Nov 18	13.3 - 18.2	15.4	24.9	17.4	20.5
Nov 21	9.4 - 14.4	11.8	16.6	14.4	30.8

The corresponding value of r_o at $\lambda = 0.5$ m are obtained from those given in the table by multiplication by $(0.5/0.633)^{6/5} \simeq 0.75$ Examination of Table 2 reveals that our values of r_o are in fair agreement with the experimental value. On the other hand AVCO's calculated values based on the measured turbulence profile are larger than the measured value by a factor of 1.5 — 2.

Note that for the three days considered the measured average values of r_o are somewhat less than the corresponding calculated values. At this point it is not clear why this should be the case, although it may just be an artifact. Although the airborne microthermal probe measurement of C_n^2 between 37 m and 2 km above the AMOS site were performed at night, the airplane was not directly above the mountain top, but instead was slightly off to one side. This suggests that the lower altitude measured values of C_n^2 probably underestimate the actual values of C_n^2 directly above the AMOS site, although it is not clear that this is the case. Based on these measured values of C_n^2 the AVCO calculated value of r_o is about a factor of two too large. We wait with anticipation for reliable low altitude C_n^2 profile measurements above the AMOS site (i.e., from the NOAA acoustic sounder). On the other hand, we arbitrarily used a model of low altitude turbulence that, strictly speaking, applies (if at all) to conditions over level ground near sea level. For the values of V that applied, the contribution to r_o from turbulence in the first three kilometers above the site is about equal to the corresponding contribution from turbulence in the tropopause (See Fig. 2). On this basis we would expect that an r_o calculated with such a turbulence profile would result in too small a value. Since our calculated values of r_o are a little on the high side, we are left in a quandry. Rather than speculate we defer further discussions on this point until more data is analyzed.

Based on our results obtained for the three dates in question, we are encouraged to make further comparisons with more data.

In conclusion we are cautiously optimistic about the use of the model of C_n^2 used here to obtain phase and log-amplitude statistics. More data comparison is clearly needed until the general use of the model can be ascertained. In particular, it is very desirable to obtain wind speed data that pertain to the time and location of the experiment. We have been in contact with P. Zieske, AVCO/Maui, and he is in process of seeing what can be done for the experiments that will be performed at AMOS this spring and summer.

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